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Shear Strength Reduction due to Excess Pore Water Pressure

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ABSTRACT

Earthquake shaking causes the pore water pressure inside the soil mass to increase rabidly within a short period of time as seconds. As a result, the shear strength of the soil could be reduced significantly. The reduction in the shear strength will increase gradually as the shaking continues due to the gradual increase in the buildup of the excess pore water pressure. At a certain level of shaking, the soil mass will liquefy and could be considered as a viscous fluid.

In this paper, a mathematical expression of a reduction factor was derived to estimate the reduction in the shear strength due to the buildup of the excess pore water pressure. This reduction factor represents the ratio of the effective shear strength of the soil at a certain level of shaking and the effective static shear strength. Using Mhor's failure criteria, the shear strength at a certain level of shaking was calculated as a function of the applied horizontal and vertical acceleration coefficients produced by the earthquake shaking at the desired value of excess pore water pressure. The reduction factor was compared with some of the available dynamic triaxial and shaking table data. It was found that the derived relationship gives a good prediction of the reduction in the shear strength until the stage of liquefaction is reached. As an application, the derived expression can be used in determining the reduction in the bearing capacity at any suggested level of excess pore water pressure using certain coefficients of acceleration.

KEYWORDS

shear, strength, soil, water, pressure, seismic, earthquake, bearing, capacity.

INTRODUCTION

Building up of excess pore water pressure inside a soil or rock mass could reduce the strength of the soil to a very low value and result in unstable ground. Several reasons could cause the pore pressure to increase such as seepage due to filling of reservoirs with water, earthquake shaking of a saturated soil layer, or leakage of water from underground broken pipeline to the surrounding mass. In 1935, local seismicity increased significantly after filling of Lake Mead behind Hoover Dam on the Nevada-Arizona border. When the Koyna Dam reservoir in India was filled with water, local shallow earthquakes became common in an area previously thought to have been virtually aseismic. In 1967, five years after filling of the Koyna reservoir had begun, a magnitude 6.5 earthquake killed 177 persons and injured more than 2000 more. After construction of the High Dam, a magnitude 5.6 earthquake occurred in Aswan, Egypt where very little significant seismic activity had been observed in the 3000 years history of the area. In these cases, seismic activity appears to have been triggered by the presence of the reservoir. While the effect of the weight of the impounded water is likely to be negligible at the depths of the induced seismic activity, an increase in pore water pressure that migrates as "pulse" away from the reservoir after filling may have been sufficient to reduce the strength of the rock to the point where rupture could occur (Kramer, 1996).

Pore water pressure inside a saturated soil layer could also increase during earthquake shaking and results in a significant reduction of the soil strength. At certain level of pore water pressure, the soil will completely loose its strength; this phenomenon is termed liquefaction (Mogami and Kubo, 1953). As a result, large earthquake damages could develop including flow failures of dams, slopes, and foundations, lateral spreading of abutments, foundations, and substructures, and sand boils. However, soil deposits that are susceptible to liquefaction are formed within a relatively narrow range of geological environments (Youd, 1991).

STABILITY FACTOR

As shown in Fig. 1, the shear strength of a saturated C-ϕ

soil is defined by,

$$\tau = C + \sigma_n' \tan\phi = C + (\sigma_n - U)\tan\phi \tag{1}$$

in which τ is the shear strength, C is the cohesion parameter, σ_n is the total normal pressure, σ_n' is the effective normal pressure, ϕ is the angle of friction of the soil, and U represents the hydrostatic pore water pressure which is calculated as,

$$U = \gamma_w z \tag{2}$$

where γ_w is the unit weight of water and z is the depth from the water table level to the point at which U is calculated. The incremental water pressure (ΔU) due to earthquake shaking will further reduce the ultimate shear strength (τ_{red}) (see Fig. 1) as,

$$\tau_{red} = C + (\sigma_n' - \Delta U)\tan\phi \tag{3}$$

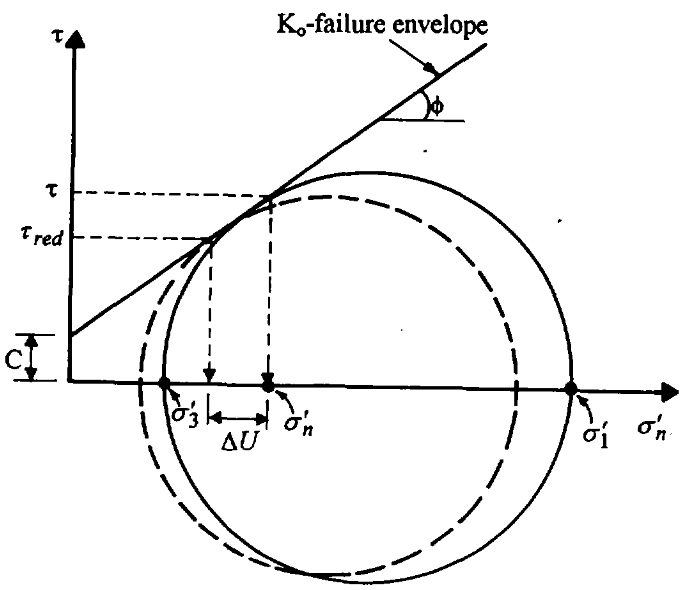


Fig. 1. Effective Mohr's circle and K_o-failur envelope.

Dividing Eqn. (3) by Eqn. (1), after dividing both by C, yields

$$\frac{\tau_{red}}{\tau} = \frac{1 + \dfrac{(\sigma_n' - \Delta U)}{C}\tan\phi}{1 + \dfrac{\sigma_n'}{C}\tan\phi} \tag{4}$$

The left side of Eqn. (4) is defined as the stability factor, $I = \frac{\tau_{red}}{\tau}$. Multiplying both sides of Eqn. (4) by $\frac{C}{\tan\phi}$ and rearranging terms gives

$$I = \frac{\dfrac{C}{\tan\phi} + \sigma_n' - \Delta U}{\dfrac{C}{\tan\phi} + \sigma_n'} \tag{5}$$

By dividing the numerator and the denominator by σ_n', one gets

$$I = \frac{\dfrac{C}{\sigma_n' \cdot \tan\phi} + 1 - \dfrac{\Delta U}{\sigma_n'}}{\dfrac{C}{\sigma_n' \cdot \tan\phi} + 1} \tag{6}$$

Assuming that the factor $F = \frac{C}{\sigma_n' \cdot \tan\phi}$, and substituting F into Eqn. (6) gives

$$I = \frac{F + 1 - \dfrac{\Delta U}{\sigma_n'}}{F + 1} \tag{7}$$

Or,

$$I = \left[1 - \frac{1}{(1+F)}\frac{\Delta U}{\sigma_n'}\right] \tag{8}$$

For cohesionless soil, C=0, the value of F=0, and Eqn. (8) reduces to

$$I = \left[1 - \frac{\Delta U}{\sigma_n'}\right] \tag{9}$$

From Mohr's circle shown in Fig. 2, the value of σ_n' can be calculated as,

$$\sigma_n' = X - R\sin\phi \tag{10}$$

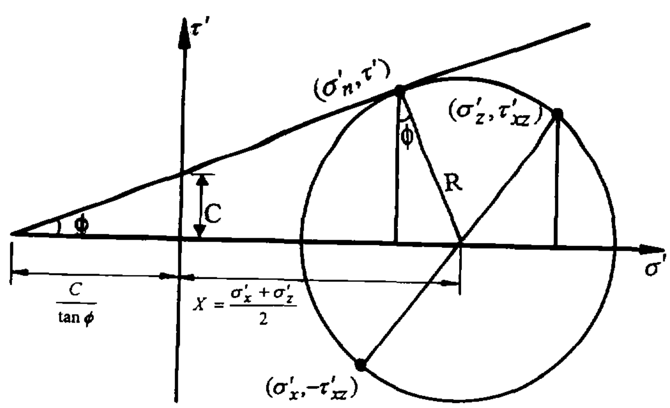


Fig. 2. Mohr Failure diagram for C-ϕ soil.

where

$$X = \frac{R}{\sin\phi} - \frac{C}{\tan\phi} \tag{11}$$

By substituting with Eqn. (11) into Eqn. (10), then

$$\sigma'_n = \frac{1}{\sin\phi}\left[R(1-\sin^2\phi) - C\cos\phi\right] \tag{12}$$

where

$$R = \sqrt{\frac{(\sigma'_z - \sigma'_x)^2}{4} + \tau'^2_{xz}} \tag{13}$$

Under free field conditions for saturated soil layer, the effective stresses σ'_z, σ'_x, and τ'_{xz} on a soil element A at depth z subjected to horizontal and vertical accelerations from an earthquake (as shown in Fig. 3) are

$$\sigma'_z = (1-k_v)\gamma' z \tag{14}$$

$$\sigma'_x = K(1-k_v)\gamma' z \tag{15}$$

and

$$\tau'_{xz} = -k_h \gamma' z \tag{16}$$

where k_h and k_v are the horizontal and vertical acceleration coefficients, respectively. Substituting of Eqns. (14), (15), and (16) into Eqn. (13) and rearranging the terms, then

$$R = \gamma' z\sqrt{k_h + (1-k_v)^2\left(\frac{1-K}{2}\right)^2} \tag{17}$$

where K is lateral earth pressure coefficient and given by Richards et al. (1990) for active case as

$$K = \frac{1+\sin^2\phi}{\cos^2\phi} - \frac{2}{\cos\phi}(\tan^2\phi - \tan^2\theta)^{1/2} \tag{18}$$

and

$$\tan\theta = \frac{k_h}{1-k_v} \tag{19}$$

By substituting of Eqn. (17) in Eqn. (12), then

$$\sigma'_n = \frac{1}{\sin\phi}\left[\gamma' z\sqrt{k_h + (1-k_v)^2\left(\frac{1-K}{2}\right)^2}\;(1-\sin^2\phi) - C\cos\phi\right]$$

..........**(20)**

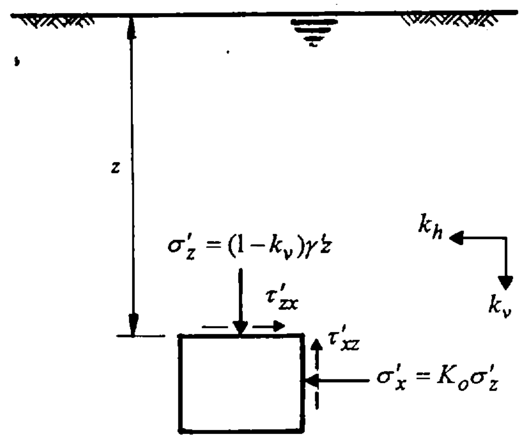


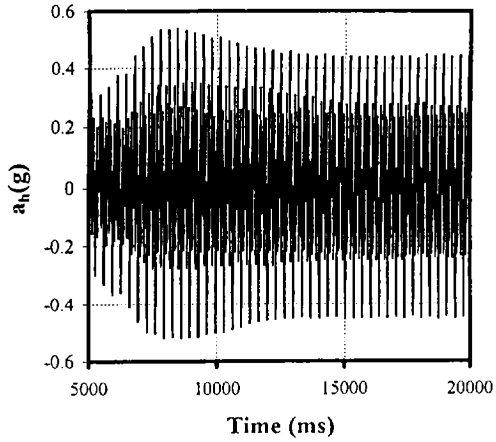
Fig. 3. Stresses on soil element due to earthquake.

By referring to Eqn. (8), when the value of the stability factor is equal to one, there is no effect of the pore water pressure on the stability of the soil layer except the one due to the hydrostatic water pressure. However, as the excess pore water pressures builds up, the stability factor becomes lower than one, and hence the stability of the soil layer starts to decrease. At high value of buildup excess pore water pressure, the value of the stability factor becomes equal to, or even less than zero at which the soil reaches a state of complete liquefaction and the soil can be treated as a viscous fluid with low shear strength.

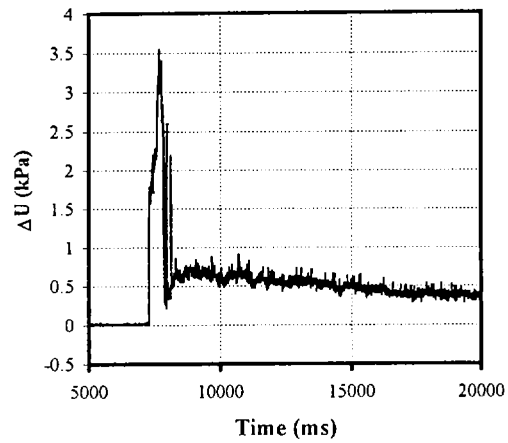
CALCULATIONS

The stability factor can be calculated for any soil layer that is subjected to earthquake shaking using Eqn. (8). Al-Karni (1993) conducted experimental tests on saturated sandy soil layer having an angle of friction of 41° and relative density of 0.67. The soil sample was shaken at horizontal acceleration of 0.45g for about 45 sec as shown in Fig 4a. The degree of saturation of the soil layer was almost 100% and the water table was at zero depth of the layer surface. The measured excess pore water pressure was high during the first cycles and then decreased gradually. This behavior is due to the ability of water to dissipate from the soil mass and the allowance of the sand to get denser. By calculating the stability factor of this soil layer at this level of shaking and at the location of measurement using Eqn. (8), it could be seen from Fig. 3c the soil has lost its strength completely at early stage of shaking where the stability factor drops below one. Due to the dissipation of the water with time, the stability began to increase as a result of reduction of the excess pore water pressure.

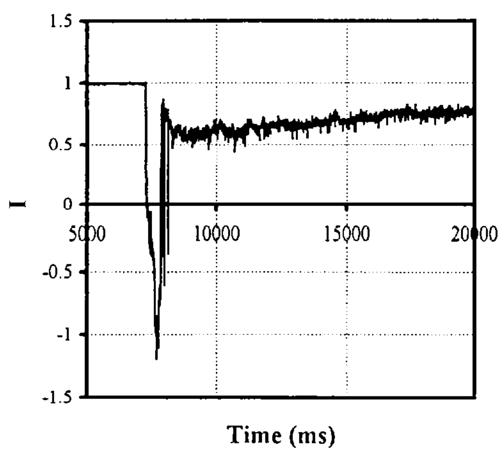
The stability factor of Eqn. (8) can be calculated also for a sample under cyclic triaxial loading. The experimental results



(a)



(b)

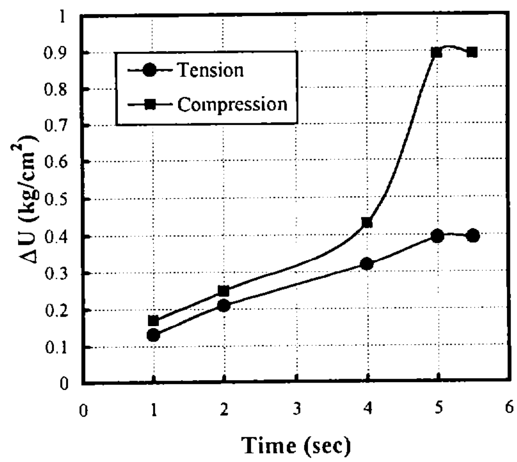


(c)

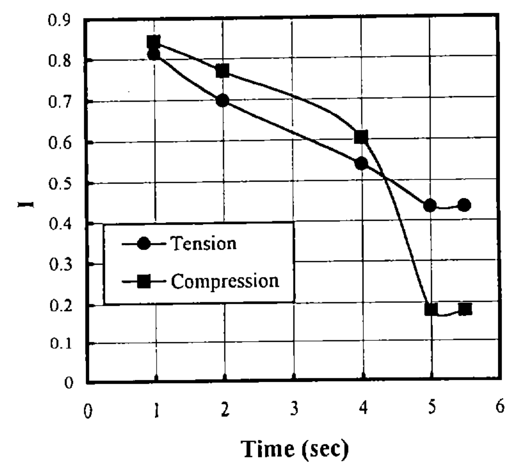
Fig. 4. (a) variation of applied horizontal acceleration with time, (b) variation of measured excess pore water pressure with time, (c) variation of the calculated stability factor with time.

of a triaxial cyclic test on loose sample of Sacramento sand that was run by Seed and Lee (1961) was used here. The variation of the stability factor with time of loading is shown in Fig. 5. This figure shows that the soil had lost its strength to a high degree when the water pressures increased to the level of the confining pressure.

The above results show that Eqn. (8) is giving a good measurement of how the soil strength changes with the changes in the excess pore water pressure. Thus the stability factor could be used as a useful factor in determining the reduction in bearing capacity as shown below.



(a)



(b)

Fig. 5. (a) measured excess pore water pressure during cyclic loading, (b) calculated stability factor.

SEISMIC BEARING CAPACITY

The seismic bearing capacity factors described by Budhu and Al-karni (1993) can be used to modify popular static bearing capacity equations (Terzaghi, 1943, Meyerhof, 1963, Hansen, 1970, Vesic, 1973). For example, the Meyerhof bearing capacity equation for vertical load can be modified to become a general equation to include seismic effects as follows:

$$q_{uE} = CN_{cS}s_c d_c e_c + q_f N_{qS}s_q d_q e_q + 0.5B\gamma N_{\gamma S}s_\gamma d_\gamma e_\gamma \qquad \text{.......... (21)}$$

where q_{UE} is the ultimate seismic bearing capacity, C is soil cohesion, N_{cS}, N_{qS}, $N_{\gamma S}$, are static bearing capacity factors, s and d are shape and depth factors, q_f is the overburden pressure, B is the footing width, γ is the unit weight of the soil, and e_c, e_q, and e_γ are the seismic factors calculated from Budhu and Al-karni (1993) as

$$e_c = \exp\left[-4.3k_h^{(1+D)}\right] \qquad (22)$$

$$e_q = (1-k_v)\exp\left[-\left(\frac{5.3k_h^{1.2}}{1-k_v}\right)\right] \qquad (23)$$

$$e_\gamma = (1-\frac{2}{3}k_v)\exp\left[-\left(\frac{9k_h^{1.1}}{1-k_v}\right)\right] \qquad (24)$$

where D = C/(γH) and H is the depth of the failure zone from the ground surface given as

$$H = \frac{0.5B}{\cos\left(\frac{\pi}{4}+\frac{\phi}{2}\right)}\exp\left(\frac{\pi}{2}\tan\phi\right) + D_f \qquad (25)$$

where D_f is the depth of the footing.

In Eqn. (21), the effect of excess pore water pressure due to earthquake shaking is not considered. Such an effect can be considered by replacing the values of the strength parameters (C and ϕ) by reduced values due to the increase of excess pore water pressure. From the definition of $I = \frac{\tau_{red}}{\tau}$, then

$$\tau_{red} = I\cdot\tau = I\cdot(C + \sigma_n' \tan\phi) \qquad (26)$$

or by using the reduced parameters,

$$\tau_{red} = C_{red} + \sigma_n' \tan\phi_{red} \qquad (27)$$

where C_{red} is unlikely to reduced below 80 percent (Seed and Chan, 1966). By assuming C_{red}=0.8 C, and equating Eqn. (26) with Eqn. (27), and rearranging the terms, then

$$\phi_{red} = \tan^{-1}\left[(I-0.8)\frac{C}{\sigma_n'} + I\cdot\tan\phi\right] \qquad (28)$$

By using the values of C_{red} and ϕ_{red}, the ultimate seismic bearing capacity (q_{UE}) under the effect of the excess pore water pressure can be calculated from Eqn. (21) as shown in the example below.

EXCESS PORE WATER PRESSURE

The value of excess pore water pressure (ΔU) that is expected to generate during an earthquake is a function of the soil properties and the duration of and intensity of the shaking. The accuracy of estimating the values of seismic shear strength τ_{red} and the apparent angle of friction ϕ_{red} will depend on how precise the induced seismic pore water pressure may be estimated in the soil deposit during the strong ground motion. According to the knowledge of author, at present, no information is available concerning measurements of pore water pressure in the field induced by seismic waves that may be used to calibrate theoretical or semi-imperial concepts. Procedures have been developed for estimating the excess pore water pressure as given, for example, by Zeevaert (1983). Near ground surface in a saturated sand layer that has a total depth that is large relative to footing size, Edinger (1989) suggested that the maximum value of ΔU would approach:

$$\Delta U = b\overline{P}_v k_h \qquad (29)$$

where $\overline{P}_v$ is the effective overburden pressure, and b=2/3 to 4/3. The value of b=4/3 represents a sand saturated to ground surface; b=2/3 represents saturation to level below the footing bearing elevation. However, no such a relationship is suggested for C-ϕ soil.

EXAMPLE

If a soil deposit has the value of C=25 kN/m^2, ϕ=30° and γ_{sat}=18.5 kN/m^3 is expected to be subjected to an earthquake shaking with k_h=0.25 and k_v=0.1, then the calculated seismic bearing capacity at zero excess pore water pressure for square footing with a side length of 1 m, depth of embedment of 1 m, and static safety factor of 3 is equal to 1208.12 kN/m^2 with seismic safety factor (F_{sE}) of 1.76 (where $F_{sE}=q_{UE}/q_{all(static)}$, and $q_{all(static)}$ is the allowable static bearing capacity). Now let us consider the effect of the excess pore water pressure in calculating the seismic bearing capacity. By assuming that Eqn. (29) is valid for the given C-ϕ soil in this example, the estimated excess water pressure was found to be equal to 7.58 kN/m^2. Then, the calculated stability factor was found to be equal to 0.644 and the reduced soil parameters C_{red} =0.8 C=20 kN/m^2 and ϕ_{red}=28.78°. By using these reduced soil parameters, the calculated seismic bearing capacity according to Eqn. (21) was found to be equal to 879.65 kN/m^2 with a seismic safety factor of 1.28. This example shows that the procedure suggested here is able to give an estimation of the reduction of the seismic bearing capacity due to the buildup of excess pore water pressure. However, a testing program is needed for calibrating this procedure.

CONCLUSSIONS

The stability of a saturated soil layer subjected to earthquake shaking could be reduced significantly due to the buildup of excess pore water pressure. This reduction in soil stability is due to the reduction in the shear resistance. A stability factor was derived here as the ratio of the reduced shear strength to the static shear strength as a function of the applied horizontal and vertical acceleration coefficients. The variation of the stability of a sandy soil layer with time, which was subjected to horizontal shaking in the laboratory, was calculated as well as the stability of a triaxial soil sample subjected to cyclic triaxial loading. The derived stability factor was used also to calculate the reduction in seismic bearing capacity. Based on the results of this study, the following points could be considered:

1. The stability factor is a useful tool for measuring the stability of saturated soil layer due to the effect of excess pore water pressure when the soil layer is subjected earthquake shaking.

2. The stability factor can be used in simple procedure to determine the reduction in seismic bearing capacity of saturated soil that is subjected to earthquake shaking.

3. Accurate relationship for the determination of the excess pore water pressure, as a function of soil properties and ground motion properties, is needed for accurate determination of the stability factor and then reduction in the soil shear strength.

4. Extensive testing program on seismic bearing capacity for calibrating the theoretical analysis is required.

5. Running of finite element analyses using advance constitutive models for solving the seismic bearing capacity will be helpful in calibrating the simple limit analysis procedure.

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